MINERvA in the Medium Energy NuMI Neutrino Beam

1. *Name:* Main INjector ExpERiment to measure ν-A Interactions (MINERvA)
2. *Physics Goals*
    a. *Primary:* to study the effect of the nucleus on the exclusive neutrino and antineutrino interaction channels that are important for current and future oscillation experiments
    b. *Secondary:* to test the role of quark flavor in the EMC effect using neutrino and antineutrino deep inelastic scattering.
3. *Expected location of the experiment/project:* NuMI Beamline Near Detector Hall
4. *Neutrino source:* NuMI Beamline
5. *Primary detector technology:* Solid scintillator and multi-anode phototubes
6. *Short description of the detector:* Segmented solid scintillator with interleaved layers of passive target material, followed by a magnetized iron spectrometer (MINOS Near Detector).
7. *List key publications and/or archive entries describing the project/experiment:*
    a. MINERvA's physics program in the Medium Energy Beam is described in detail at http://minerva-docdb.fnal.gov/cgi-bin/ShowDocument?docid=10568
    b. Design, Calibration and Performance of the MINERvA Detector, Nucl. Inst. and Meth. A743 (2014) 130. http://dx.doi.org/10.1016/j.nima.2013.12.053
    c. The MINERvA Data Acquisition System and Infrastructure, Nucl. Inst. and Meth. A694 (2012) 179. http://dx.doi.org/10.1016/j.nima.2012.08.024
    d. Measurement of Ratios of ν_μ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energies 2-20GeV, Phys. Rev. Lett. 112, 231801 (2014). http://arxiv.org/abs/1403.2103
    e. Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at E_ν~3.5 GeV, Phys. Rev. Lett. 111, 022502 (2013). http://arxiv.org/abs/1305.2243
    f. "Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Ev~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013). http://arxiv.org/abs/1305.2234
    g. Other results from the Low Energy dataset submitted for publication can be found at: https://neutrino.otterbein.edu/Glaucus/public/publications.cgi
8. Collaboration
    a. Institution list: Centro Brasileiro de Pesquisas Fisicas, University of Chicago, Fermilab, University of Florida, University of Geneva, Universidad de Guanajuato, Hampton University, Inst. Nucl. Read. Moscow, Massachusetts College of Liberal Arts, Northwestern University, Otterbein University, Pontificia Universidad Catolica del Peru, University of Pittsburgh, University of Rochester, Rutgers University, Tufts University, University of Minnesota at Duluth, Universidad Nacional de Ingenieria, Universidad Tecnica Federico Santa Maria, College of William and Mary
    b. Number of present collaborators: ~75, but about 40FTE's because of other committments
    c. Number of collaborators needed: 85 (or 50FTE's): We have more physics analyses in our data sets than we have people to do those analyses, so getting more postdocs and graduate students would make a big difference in our physics output. The collaboration spends a considerable fraction of its effort on detector and computing operations, so postdocs or laboratory staff would be a big help here.

9. *R&D (The listed here are our physics goals in the Low Energy data that was taken before 2013, and serve as R&D for current and future oscillation experiments as well as for MINERvA's medium energy data set)*
    a. *Topics that are being investigated:*
        i. Electron Neutrino Charged Current Quasi-elastic (CCQE) Cross Section
        ii. Double Differential CCQE cross sections on plastic for neutrinos and antineutrinos
        iii. CCQE on different nuclei
        iv. Neutrino Deep Inelastic Scattering Cross Section Ratios
        v. Neutrino/Antineutrino total charged current cross section ratio
    b. *Topics that have been completed (or nearly completed):*
        i. Quasi-elastic differential Cross section ($d\sigma/dQ^2$) and CCQE vertex energy measurements (neutrino and antineutrino) in the Low Energy beam
        ii. Inclusive and Coherent pion production (neutrino and antineutrino)
        iii. Charged Current Cross Section ratios on Fe/CH, Pb/CH, C/CH for antineutrinos
        iv. Measurements of the NuMI Flux using neutrino-electron scattering
        v. Predictions for NuMI flux given hadron production measurements
    c. *Which of these are crucial to the experiment:* these are all important measurements in the Low Energy beam which will inform the analyses in the Medium Energy data that is now being collected. The reconstruction tools that are developed in the earlier data set can be used on the current data set with minimal modifications but do need to be extended to the nuclear target region where only the Medium Energy beam will provide the required statistics.
    d. *Time line:* took Low Energy neutrino and antineutrino data from November 2009 through April 2012, taking Medium Energy neutrino and antineutrino data from September 2013 through 2 years of antineutrino running.
    e. *Benefit to future projects:* MINERvA is measuring both the signal and background processes that are important to neutrino oscillation experiments on a variety of different nuclei in a broad band neutrino beam. By studying these interactions across many energies and nuclei we will provide the theory with the input needed to produce the best description of the nucleus.
10. *Primary physics goal expected results/sensitivity:*
    a. MINERvA expects to collect several thousand events each of several different kinds of exclusive neutrino interactions on Pb, Fe, and C and factors of 10-50 more on scintillator (CH) to make direct comparisons between different nuclei of a range of exclusive channels at better than the 10% statistical level. The experiment produces a large variety of measurements which all have different systematic uncertainties and sensitivities. Channels studied include the quasi-elastic interaction, charged current single and coherent pion production, through deep inelastic scattering. See reference a) in the list of publications above for more details.
    b. *List the sources of systematic uncertainties included above:* The above paragraph describes the statistical uncertainties expected. The dominant uncertainty in the Low Energy analysis is due to uncertainties in the absolute neutrino flux. Given the neutrino-electron scattering rates in the Medium Energy beam and a Low Energy beam analysis, an overall neutrino flux uncertainty of better than 6% is achievable with $6x10^{20}$ protons on target (POT) in neutrino mode. Other significant systematic uncertainties come from imperfect knowledge of final

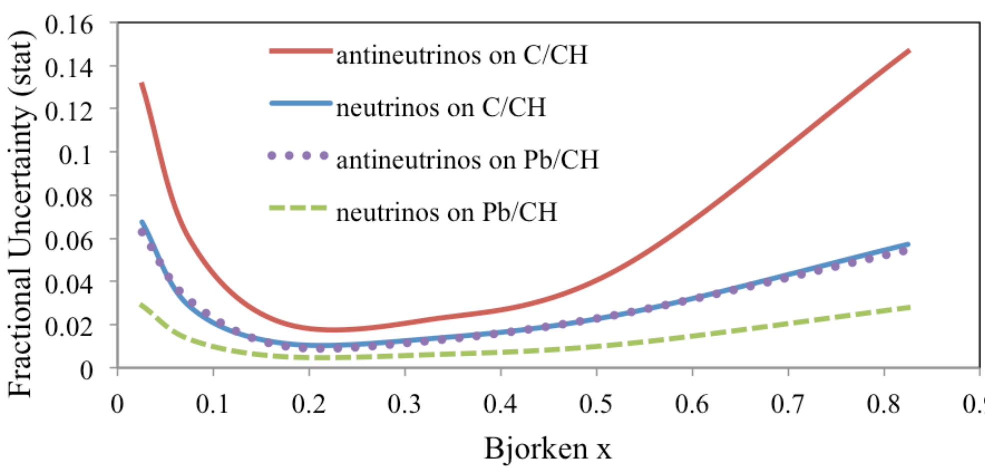
state hadron rescattering in the detector, and backgrounds from other neutrino interactions that cannot be completely constrained by sideband techniques.

c. *List other experiments that have similar physics goals:* The T2K ND280 program has a goal of measuring the cross section ratios for Water to Scintillator but will do so at 700MeV in a narrow band beam. Other experiments (LAr1ND, MicroBooNE, NOvA) can measure some of these specific interaction channels but will do so on a single target nucleus and at lower energies.

d. *Synergies with other experiments:* these measurements will provide input that will be needed by any neutrino experiment in the few GeV range that needs to measure neutrino energies: these include T2K, NOvA, ELBNF. There is also a synergy with the electron scattering experiments at Jefferson Lab who have been studying the effect of the nucleus by using several different targets in one experimental setup, on several different processes (elastic scattering through DIS).

11. *Secondary Physics Goal*

a. *Expected results/sensitivity:* One example of a new analysis that the NuMI Medium Energy era makes possible is neutrino and antineutrino charged current DIS cross Section ratios for Iron, Lead, and Carbon compared to plastic. This probe of nuclear effects in the medium energy beam has the sensitivity to demonstrate that dynamics in the nucleus connected to quark flavor cause the EMC effect. The plot below shows the statistical uncertainties on the ratios for lead and for carbon, and the uncertainties for iron to scintillator are similar to those of the lead to scintillator. The statistics shown assume 10×10^{20} POT in neutrino mode and 12×10^{20} in antineutrino mode. The expected size of the effect ranges from a few per cent at low x to 10-20% at high x.



In the plot above only the statistical errors are shown. Based on a similar analysis in the Low Energy beam, the detector, flux, and cross section systematics would be at the few per cent level (described in Phys. Rev. Lett. 112, 231801 (2014) (http://arxiv.org/abs/1403.2103)

b. *List other experiments that have similar physics goals:* There is no other experiment that can make side-by-side comparisons of neutrino interactions on more than one target nucleus. By comparing different nuclei directly in the same detector, systematics cancel and few per cent level precision can be reached. Proposed Jefferson Lab experiments probe this physics either by studying isotopes of the same nucleus (Ca40 to Ca48), or by spin-dependent studies. Evidence from both neutrino and electron scattering would be particularly compelling.

12. *Experimental requirements*

MINERvA requires another 2×10^{20}POT in neutrino mode in addition to the 4 $\times 10^{20}$POT already collected, and 12 $\times 10^{20}$POT in antineutrino mode in the NuMI beamline, which we expect would be delivered with single spill intensities of up to 6 $\times 10^{13}$ protons per pulse, and running for another 3 years from January 2015 at a minimum. The experiment also needs to maintain the MINOS near detector and the ability to process and calibrate the MINOS near detector data for use as a muon spectrometer. The experiment also receives technical support from Fermilab for MINOS near detector operations and data processing for both MINERvA and MINOS detectors, that would need to continue at current or somewhat increased levels.

13. *Expected Experiment/Project time line*
    a. *Design and development:* completed 2006-2010
    b. *Construction and Installation:* completed 2009-2010
    c. *First data:* November 2010
    d. *End of data taking:* after 12e20 POT in antineutrino mode (as early as 2018)
    e. *Final results:* 2019, or 1 year after the end of antineutrino data taking
14. *Estimated cost range*
    a. *US contribution to the experiment/project:* 15.5 M$ from DOE between 2006-2010, 0.8M$ from NSF in 2006.
    b. *International contribution to the experiment/project:* scientist effort
    c. *Operations cost:* $200k (Laboratory M&S) per year plus personnel salaries for occasional detector component repair and replacement (MINERvA plus MINOS Near Detector), and collaborator salaries and travel. Not included in this of course is the cost of running the NuMI beam which is already operating for the NOvA experiment.
15. *The Future*
    a. *Possible detector upgrades and their motivation:* CAPTAIN MINERvA (see separate CAPTAIN template) is an idea to put the CAPTAIN Liquid Argon TPC in front of much of the MINERvA detector in order to measure Argon to Scintillator cross section ratios in neutrino and antineutrino beams. Note: the CAPTAIN MINERvA collaboration would unite the two collaborations and would be significantly larger than either current collaboration.
    b. *Potential avenues this project could open up:* This program provides many new measurements that will serve as input to provide much better theories to describe neutrino interactions, and much better event generators to simulate them. MINERvA already has strong connections with groups developing the GENIE neutrino event generator, as well as the T2K and NOvA oscillation experiment analysis groups.